EDDY CURRENT IMAGING USING MULTI-FREQUENCY MIXING METHODS FOR AIRCRAFT STRUCTURAL INTEGRITY VERIFICATION

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INTRODUCTION

Automated eddy current scanning of military or civilian aircraft structures is rarely performed in the field. Manual tests usually are performed by simply placing or sliding a probe across the interrogated surface, while an eddy current instrument's impedance plane is observed for flaw responses. Scanning and imaging technologies, however, have sparked considerable interest and investigations in the feasibility of using automated eddy current nondestructive testing (NDT) methods in the aircraft community. The scanning system's intent is to provide the inspector with a rapid and sensitive method to identify locations of potential or immediate concern. Automated imaging techniques offer several advantages over conventional methods, including better reproducibility, reportability and detectability. Recent strides in these areas have dealt mostly with the detection of corrosion in thin skin structures between the fasteners. Wing structures, however, typically consist of much thicker material, where sub-surface corrosion in overlapping joints or fatigue cracks can occur under the fasteners. These flaws may not extend to the surface nor beyond the fastener before they become critical, thus making visual (including enhanced) techniques ineffective.

For second layer corrosion detection, a varying gap size due to plate separation produces a very similar impedance plane response to that from material loss due to corrosion. This is especially important in thin skin structures, such as fuselage lap-splices since corrosion products force the skins apart between the fasteners, thus causing "pillowing". This problem has been addressed in the past with the use of dual frequency mixing methods. [1,2,3] Although variable air gaps in thick skin structures are typically not as pronounced as in fuselage lap splices, the complications and reduced sensitivity introduced by the larger material depths and fastener interference makes corrosion and crack detection under fasteners much more difficult for eddy current scanning methods.

This paper presents eddy current C-scan results of simulated wing joint specimens having either cracks or second layer corrosion under installed fasteners. A modified frequency mixing approach is presented as a solution when inspecting under fasteners.

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EXPERIMENTAL PROCEDURE

Exfoliation Corrosion and Fatigue Crack Specimens

Aluminum alloy plates of the same thickness as found in the wing plank joints for the upper wing skin of the Canadair CL-601 (Challenger) were selected as the exfoliation corrosion test subjects for this study. Although real wing planks are machined from 7475-T7351 plate, specimens of 7075-T6 sheet 0.175" thick, approximately 10"x6", were prepared with simulated corrosion sites in the form of flat-bottomed holes, as shown in Figure 1(a). The specimen material was substituted to ease the development of the corrosion sites in these holes. The diameters of the holes in inches, from left to right are 1.00, 0.875, 0.625, 0.625, 0.50, 0.375 and 0.313. The depth of the holes in the top row is 0.00", in the second row 0.020" and in the bottom row 0.060". The remaining surface was then painted, after which the specimens were exposed to a standard corrosion solution (as per the EXCO exfoliation test in ASTM G34) for 28 hours, followed by rinsing, cleaning, and metallographic examination. The average depths of the unprotected, "naturally corroded" holes in each row were then measured at 0.006", 0.028" and 0.072" respectively. The details of the specimen design and method of preparation have been reported elsewhere. [4] These specimens were fastened to blank sheets with nonferrous Ti Hi-Lok fasteners having 0.375" diameter heads to simulate exfoliation corrosion in the second layer, under installed fasteners, as shown in Figure 2(a).

The fatigue crack specimens were manufactured from 0.330" thick 7075-T651 aluminum plate. As shown in Figure 1(b), each specimen contains three 0.25" fastener holes, and each fastener hole typically contains two fatigue cracks at the countersink, at the faying surface or at the mid-bore of the fastener hole. The fastener hole and crack geometry are shown in Figure 2(b). Fatigue cracks were generated by first drilling a small pilot hole, fatiguing the specimen under axial loading followed by boring the final fastener hole and countersink. All fatigue cracks were measured microscopically during the crack generation process and span a range of radial crack lengths from 0.008" to 0.300". The details of the preparation of these specimens have been reported elsewhere. [5] A second unflawed plate was fastened to these specimens with Ti high-torque fasteners having 0.5" diameter heads to represent a wing structure with cracks under the fasteners in the first layer. Cracks under 0.125" long are overshadowed by the fastener head and are not surface breaking.

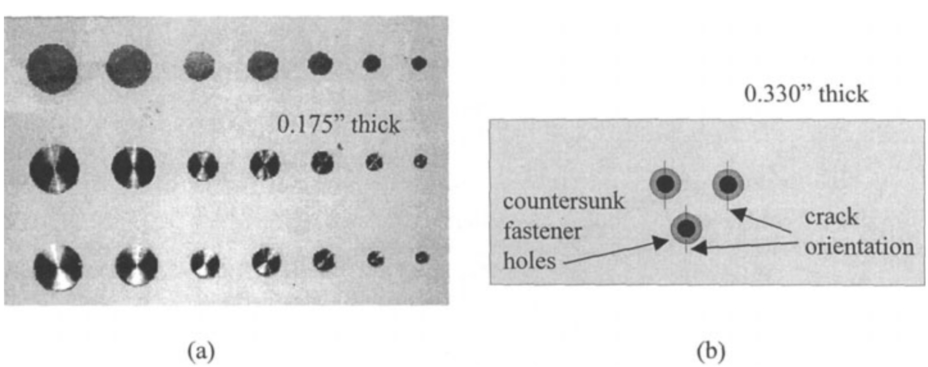
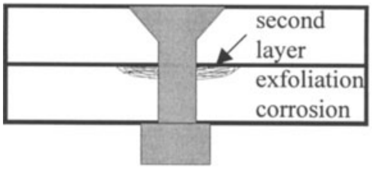
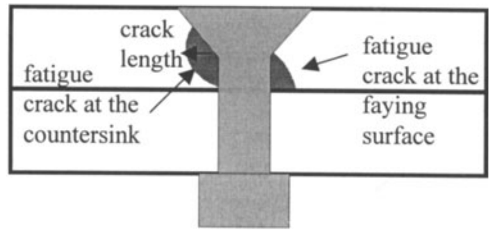


Figure 1. (a) Painted sheet of 7075-T6 aluminum prior to exposure and (b) diagram of a typical fatigue crack specimen, both before fasteners are installed.



(a)



(b)

Figure 2. Schematic diagram of (a) exfoliation corrosion in the second layer under a fastener, and (b) a countersink and a faying fatigue crack under a fastener.

Scanning Procedure

The set-up is shown schematically in Figure 3. Two reflection probes were used in the experiments: one 0.625" diameter probe for the corrosion specimens with a range of 100 Hz to 10 kHz, and the other 0.5" diameter for the crack specimens with a range of 500 Hz to 15 kHz. These were connected to a Zetec MIZ-40 Eddy Current Instrument capable of performing up to four different frequency measurements simultaneously. Each plate was scanned using an automated 2-axis table scanner controlled by Winspect™ data acquisition and motor control software with a 16 channel digitizer, of which only eight were connected to the eddy current instrument. It is important to differentiate this multi-frequency set-up from an actual multi-frequency eddy current technique. In this case, four frequencies are captured at once producing four different scans; however, the analysis is performed one frequency at a time, making it a single frequency method. The implementation of this multi-frequency set-up simply reduced the number of required scans.

The impedance plane responses in magnitude and phase are digitized into a 0 to 255 intensity scale, while the sample is scanned in a raster pattern. A 10x6 inch plate typically requires up to 15 minutes to scan with a 0.039" (1mm) resolution. The software displays the data from the 2-D scan by mapping the intensity scale onto an arbitrary color scale (or, alternatively, a grayscale), resulting in a 256 color (or, shades of gray) C-scan image for each test and frequency. Since the instrument's phase is selected to maximize the flaw responses in the vertical, or 90 degree, direction, only the vertical amplitude data will be imaged. Note that although phase data can also be displayed, little information is found to be useful in the C-scan images of this study.

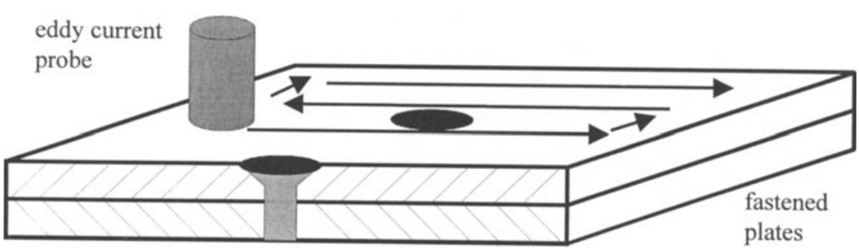


Figure 3. An automated mover scans the eddy current probe over the fastened plates

RESULTS AND OBSERVATIONS

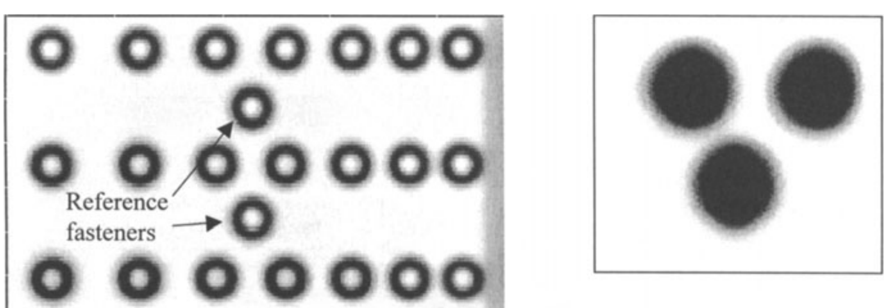
Single Frequency Results

A typical single frequency scan of the corrosion specimens is shown in Figure 4(a). The fasteners, including the two reference fasteners situated at non-corroded sites between the rows, have the effect of producing large impedance plane responses that are in-phase, or close to in-phase, with corrosion signals. Hence, most of the corrosion indications become masked in the impedance plane, as well as in the amplitude C-scan image. Consequently, it becomes very difficult to separate the fastener signal from the corrosion signal when the latter originates directly beneath the fastener head.

Similarly, a single frequency scan of a specimen with cracks at the countersink is shown in Figure 4(b). Predictably, there are no obvious indications of the cracks due to the large signals from the fasteners. Both of these results dramatically illustrate the major problems of inspecting aircraft structures for flaws under fasteners when using eddy current raster scanning methods.

Dual Frequency Mixing

One common method of minimizing noise responses involves using the instrument's built-in dual frequency mixing capability. Since defects and other material characteristics each produce signal responses that vary differently with frequency, the instrument mixes the properly selected dual frequency signal responses in a way (usually by vector subtraction) that enhances the hidden flaw signal while minimizing the noise. The discriminating features between the noise and the flaw signals that are brought out of this operation are based on the slight phase shifts and amplitude changes between the two frequency responses. This method has been demonstrated in the past to reduce the effects of air gap variations between plates. [1,2,3] A similar procedure was employed here to reduce the effects of fasteners.



900 Hz scan of 7075-T6 corrosion specimen

(a)

1 kHz scan of specimen with cracks under fastener

(b)

Figure 4. Single frequency scan results of both corrosion and crack specimens

Two frequencies were selected such that the low, or primary, frequency was low enough to penetrate at least two standard depths to the expected flaw's location, and the high frequency was within 2 to 4 times the primary. The instrument was then nulled with the probe located away from any corrosion, cracks or fasteners, and the phase set to produce lift-off signals in the horizontal direction. With the probe positioned near a reference fastener, a linear scan was performed across, but slightly off-center to that fastener to keep the resulting noise signals at both frequencies within the boundaries of the instrument's screen. Scanning over the center of a fastener results in a large saturated signal that cannot be mixed effectively. Figure 5 illustrates this offset as D_{offset}. These signals were mixed using the instrument's on-board mixing functions. The probe then was scanned in a line off-center, as before, to a fastener under which it was known to have a significant amount of corrosion or a crack. The procedure was repeated with various combinations of frequencies, gains, and D_{offset} distances until the mixed signal exhibited minimal fastener signal with maximum flaw signal and phase separation. Then, the entire plate was scanned in a raster pattern, as before, with the above dual frequency set-up. Ideally, the residual fastener signal should be in phase with the lift-off signal, with both signals being perpendicular to the corrosion response. However, it was very difficult to find the parameters that achieved the best phase separations. A set-up was deemed acceptable if it could generate a corrosion signal that was over 45 degrees to the lift-off signal. [This constraint could have limitations in practice where there are significant variations in paint thickness and surface roughness.] Note that the mixing routine will cause the lift-off signal to phase shift away from the usual horizontal trajectory. Hence, it is most important to re-rotate the phase back to achieve a horizontal lift-off signal before starting the scan.

Dual Frequency Mixing Results

The advantages of frequency mixing are evident in the images of the corrosion sample shown below. Whereas the single frequency scan in Figure 4 is cluttered and dominated by the fastener signals, the mixed frequency scan of Figure 6 amplifies the corrosion signal and reduces those from the fasteners. The corrosion in this case appears as dark rings around the fasteners. The method's effectiveness is also illustrated in Figure 7 where the crack signals are clearly evident as dark areas adjacent to every hole. In both cases, the severity of the flaw (depth, or radial length) is related to the intensity, or the darkness, of the signal. Note that the fasteners cannot be completely clipped out since their signals are too large to allow a D_{offset} of zero during the mixing procedure. The method was also used on specimens that had fatigue cracks at the faying surface, with the results also shown in Figure 7. The crack sizes are given in the figures.

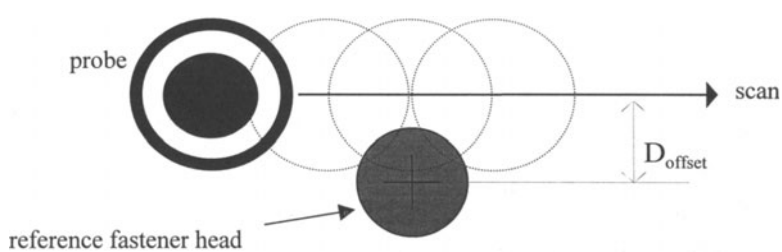


Figure 5. Offset scan over fastener

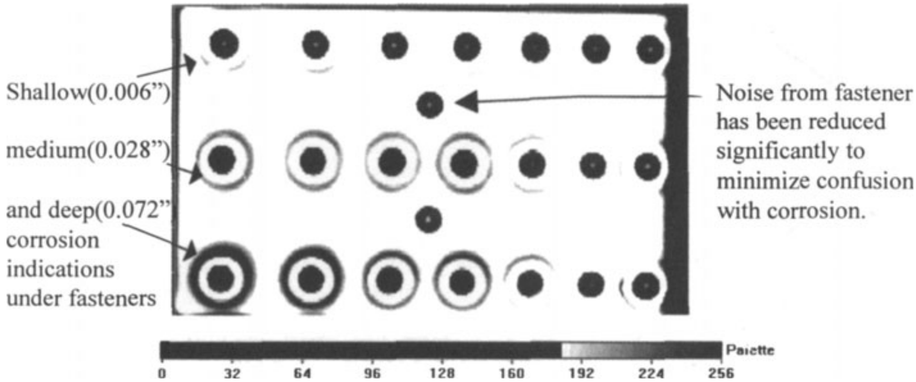
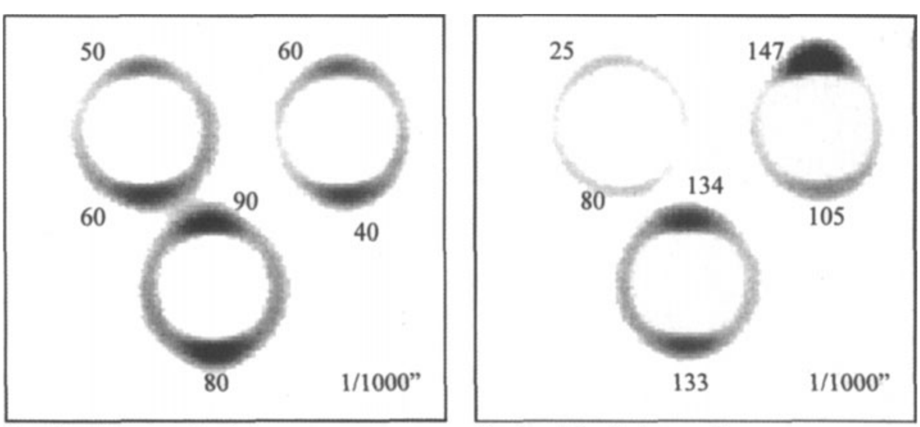


Figure 6. 2.3 kHz-900 Hz mixed frequency scan of 7075-T6 corrosion specimen

Given the appropriate frequency mix and signal range, one can easily identify those fasteners which exhibit significant amounts of exfoliation corrosion, as shown in the lower two rows of Figure 6. Note the corrosion indications are apparent down to, and including, the 0.5" diameter sites. This implies that the technique will pick up corrosion in the second layer if it extends at least 0.0625" beyond the 0.375" diameter fastener head. The scans also indicate a capability to detect relatively low levels of corrosion under fasteners, as shown in the shallow sites in the top row of Figure 6, which represent 3.4% thinning due to corrosion only. There are, however, some false indications between the two fasteners on the right of each row.

The dual frequency method was capable of detecting countersink cracks with lengths well within the shadow of the fastener head. As shown in the left side of Figure 7,



Cracks at the countersink

Cracks at the faying surface

Figure 7. 1 kHz-2 kHz mixed frequency scans of specimens with cracks under fasteners

the smallest detectable crack was 0.040" long from the bore. Faying surface cracks are deeper in the material, hence only those over 0.100" long could be detected. Note that colored images are more effective at discerning the flaws in both cases below.

It is worthwhile noting that the indicated areas of corrosion, crack lengths and fastener head sizes in the C-scans are larger than their actual size due to the large diameter of the probe. The crack indications are especially "smeared out" due to the diffusive nature of the eddy currents. Better resolution can be achieved from smaller probe diameters, but this usually results in weaker signals and less depth of penetration. Furthermore, since these eddy current images are only amplitude representations, they do not display information about the entire signal. The phase changes, for example, can provide complementary information when displayed alone, and enhanced images when properly combined with the amplitude data. In this study, however, this was not attempted since the phase images were very noisy due to the very low frequencies and subsequently low sensitivities. In their present state, the images are useful when the inspection is set up and calibrated to detect a pre-determined range of defects, presented in terms of a meaningful color or gray scale, in a constrained configuration. Therefore, with calibration scans, the method could be used to determine a threshold intensity value above which any indications in future scans on similar inspectable components would signify corrosion or cracks beyond those acceptable limits.

CONCLUSIONS

Single frequency eddy current imaging methods are adequate for detecting second layer corrosion in thick, two-layer Al-alloy wing planks if first layer corrosion, varying air gaps, or fasteners are not present. Frequency mixing is essential, however, for detecting second layer corrosion or fatigue cracks under installed fasteners in thick structures. With the appropriate frequency selections, corrosion under the fasteners in the subject specimens were observable from the scans by minimizing the strong signals from the fasteners. In this case, the smallest detectable corrosion site had a diameter of 0.5" and a depth of 0.006", corresponding to 3.4% thinning, located in the second layer under a fastener with a 0.375" diameter head. In the present study it was not possible to detect second level corrosion if it was confined to an area smaller than that of the fastener head.

Similarly, cracks emanating from either the countersink or from the fastener hole at the faying surface were detected with the dual frequency mixing method. Fatigue cracks over 0.040" long at the countersink were discernible from the resulting images. Hence, frequency mixing can be combined with automated eddy current image scanning methods to inspect thick skin aircraft structures quickly and reliably.

FUTURE WORK

Future improvements to these multi-frequency scanning methods may include extracting more information from the entire signal, rather than just the vertical signal, such as phase changes that could be used to provide more flaw depth information. Furthermore, the effects of measuring corroded areas smaller than the coil itself must be closely examined to develop a better understanding of their relationships for improved flaw characterization. Lastly, the method will most likely have some limitations when applied to specimens with ferrous fasteners, hence further developments will be made for this case.

REFERENCES

1. J.G. Thompson, "Subsurface Corrosion Detection in Aircraft Lap Splices Using a Dual Frequency Eddy Current Inspection Technique", Materials Evaluation, December 1993, pp 1398-1401.

2. D.J. Hagemaier, "Automated Eddy Current Scanning of Aircraft for Corrosion Detection", Materials Evaluation, January 1994.

3. W.D. Chevalier, “Dual Frequency Eddy Current Testing for Second Layer Corrosion”, 1993 ATA NDT Forum, September 22, 1993.

4. R. Kearsey, B. Lepine, R.T. Holt and G. Dziub, “Detection of Corrosion Under Fasteners in Simulated Wing Joints Using Eddy Current Scanning Techniques”, NRC/Institute for Aerospace Research Report LTR-ST-2059, October 1996.

5. M. Larocque and M. Yanishevsky, “CF116 Upper Wing Skin Golden Triangle POD Specimens”, Quality Engineering and Test Establishment Report No. A013692, December 1993.